MECHANICAL, THERMAL AND TRIBOLOGICAL BEHAVIOUR OF GLASS FIBRE/ABS, CARBON FIBRE/ABS AND THEIR HYBRID COMPOSITES USING HYBRID FABRICATION TECHNIQUE

A SYNOPSIS

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1. INTRODUCTION

The composite materials have pushed the limits because of their high performance and lightweight nature, thereby gaining application in all sector. Moreover, the need for sustainable choice have created demand in augmented use of thermoplastic composites. Recently, composites with synthetic fibres have replaced traditional materials such as iron, steel and aluminium as their alternate solution because of their advantages such as enhanced physical performance, design flexibility, corrosion resistance and lightweight. Synthetic fibres have started gaining demand in the modern era due to their physical behaviour, ease in fabrication, corrosion resistivity, and the better strength-to-weight ratio. Currently, glass fibre (GF) and carbon fibre (CF) are of high demand as they are versatile and industrially sought of all the fibres. Glass fibres are low in price and exhibit better properties such as hardness, resistance to chemicals, being transparent, stability, inertness, high strength-to-weight ratio, flexibility and stiffness. Carbon fibres are more expensive than glass fibres and exhibit improved properties such as tensile strength, resistance to chemicals, resistance to high temperature with low coefficient of thermal expansion, and stiffness.

Amongst the fabricated techniques, 3-dimensional printing (3D) is one of the most popular rapid prototyping methods. The 3D printing is a process used to make 3D objects using computer software and computer-aided design. ABS is amorphous and considered as an effective toughener. Hot compression moulding is the most sought and cost-effective fabrication technique for achieving high-strength composites [1], [2].

The feasible options are to hybridize manufacturing techniques as well as to hybridize one with another synthetic fibre in the same matrix. All these could contribute to cost savings, increased modulus, strength, corrosion resistance, enhanced thermal stability and improved tribological performances.

This study implemented a hybrid manufacturing technique to fabricate the composite samples, such as fused deposition modelling and hot press moulding technique. The composite samples were prepared using glass fibre, carbon fibre and ABS and the samples were analysed for mechanical, thermal and tribological performances.

2. LITERATURE REVIEW

Literature survey was done on the topics of synthetic thermoplastic fibre reinforced plastics, 3 D printing, hot compression and the performances achieved in terms of mechanical, thermal and tribological behaviour.

Mahesh et al. [3] explored the tensile, flexural and impact behavior of GF/ABS composites fabricated by hot press moulding technique. They reported that 40:60 (fibre to resin ratio) as the optimum condition to achieve improved performance in terms of tensile, flexural and impact behaviour of the composite.

Ning et al. [4] examined the mechanical properties of CF/ABS composites by varying fibre loadings from 0wt.% to 15wt.% and by varying the process parameters in the FDM technique. Results reported that the mechanical properties were observed to increase until 5wt.% of fibre loading, followed by decreased properties. The tensile properties were observed to be high when the raster angle of [0, 90] was maintained. Then, the other parameters, such as infill speed, nozzle temperature and layer thickness, were maintained at 25mm/s, 220°C and 0.15mm, respectively.

Ning et al. [5] fabricated carbon fibre/ABS composites using a plastic extruder followed by the FDM technique. Further, the composite samples were subjected to mechanical properties by varying the fibre loadings from 3% to 15%. Results reported that carbon fibre-reinforced composites exhibited improved properties in tensile strength and Young's modulus. However, toughness, yield strength and ductility were found to be decreased. Regarding the influence of fibre loading, 5wt.% of carbon fibre-loaded composites showed higher values in tensile strength, and 7.5wt.% of carbon fibre-loaded composites were higher in Young's modulus.

Wang et al. [6] fabricated PLA and glass fibre/PLA composites using the fused deposition modelling technique and compared their mechanical properties. The results reported that the continuous glass fibre reinforced composites exhibited 400% and 204% enhancements in tensile and flexural strengths than virgin PLA matrix.

Xie et al. [7] fabricated polyacrylonitrile (PAN)/CF-reinforced thermosetting polymer using a hot compression technique. Results revealed that optimum conditions for improved performance in terms of tensile, bending and interlaminar shear strength (ILSS) were achieved at 150˚C compression temperature, 20 min holding time under a pressure of 50 T, 3.5˚C/min cooling rate, and 80˚C mould-opening temperature.

Adeniran et al. [8] compared the mechanical and thermal performances of Polyamide/carbon fibre, and ABS/carbon fibre reinforced composites fabricated using the fused deposition modelling technique. Due to their loose morphology, the carbon fibre-reinforced ABS matrix composites were found to be superior in modulus properties. Regarding the specific heat of fusion, the carbon fibre-reinforced polyamide matrix composites were higher than the carbon fibre/ABS composites.

Hu et al. [9] fabricated short carbon fibre reinforced poly-ether-ether-ketone composites using a single screw extruder followed by a fused deposition modelling technique. Further, the fabricated samples were subjected to analyze mechanical and thermal properties by varying the nozzle diameter, processing temperatures, and infill angle. Results revealed that large nozzle diameter and increased nozzle temperature were beneficial to producing good quality composites. Regarding the mechanical properties, tensile strength and elastic modulus were improved by 59% and 169% compared to virgin polyether-ether-ketone. The thermal resistance was examined using a dynamic mechanical analysis test. The glass transition temperature (Tg) was measured using loss modulus graphs. The Tg of 148.7°C was observed for carbon fibre/ poly-ether-ether-ketone composites at 5% fibre loading.

Billah et al. [10] fabricated GF/ABS and CF/ABS reinforced composite using large area 3D printing. The DSC test was performed to investigate glass transition (T_g) and melting temperature (T_m) of ABS and ABS fibre reinforced composites. The observations reported no significant changes in T_g (107 °C) between ABS and ABS fibre reinforced composites, while a peak at second endothermic (140 °C) represents melting of processed materials as no definite melting range could not be traced due to amorphous ABS.

3. RESEARCH GAP

The following research gap was found based on the literature review.

- There has been restriction in hot compressing thermoplastics due to (i) uneven melt flow, (ii) less penetration into the gaps of fibre mats.
- There has not been any research work reported involving printing thermoplastics over fibre mat surface.
- The combination of fused deposition modelling (FDM) and hot compression moulding technique has not been explored previously.

- Examining the mechanical properties, thermal properties (particularly thermogravimetric analysis (TGA), thermomechanical analysis (TMA), Dynamic mechanical analysis (DMA) and Differential Scanning Calorimetry (DSC)) and tribological behaviour of synthetic fibre reinforced thermoplastic composites fabricated by the hybrid manufacturing technique have not been thoroughly investigated.

Overall, the research gap lies in the limited exploration of hybrid manufacturing technique (FDM followed by the hot press moulding), the lack of investigation on specific combinations of synthetic fibre reinforced thermoplastic composites, and the insufficient analysis of mechanical, thermal, and tribological properties of the pure and hybrid composites.

4. OBJECTIVES

The following are the research objectives.

- To fabricate virgin ABS samples using 3D printing.
- To fabricate Glass fibre / Acrylonitrile butadiene styrene (ABS), Carbon fibre / Acrylonitrile butadiene styrene (ABS) and hybrid Glass fibre / Carbon fibre / Acrylonitrile butadiene styrene (ABS) composites using `fused deposition modelling (FDM) followed by hot compression moulding techniques (hybrid manufacturing technique).
- To investigate the mechanical properties such as tensile, flexural, impact, and inter-laminar shear strength (ILSS) of ABS, GF/ABS, CF/ABS and GF/CF/ABS composite samples.
- To characterize the wettability behavior of ABS, GF/ABS, CF/ABS and GF/CF/ABS composite samples using contact angle measurement.
- To investigate the thermal testing such as thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), thermomechanical analysis (TMA) and dynamic mechanical analysis (DMA) of ABS, GF/ABS, CF/ABS and GF/CF/ABS composite samples.
- To investigate the tribological behaviour of ABS, GF/ABS, CF/ABS and GF/CF/ABS composite samples using dry sliding wear test.
- To investigate the adhesion between fibres and the matrix, the presence of voids, debonding, and other interfacial phenomena are examined using scanning electron microscope (SEM).

5. RESEARCH METHODOLOGY

An outline of the research methodology adopted is shown in Figure 5.1.

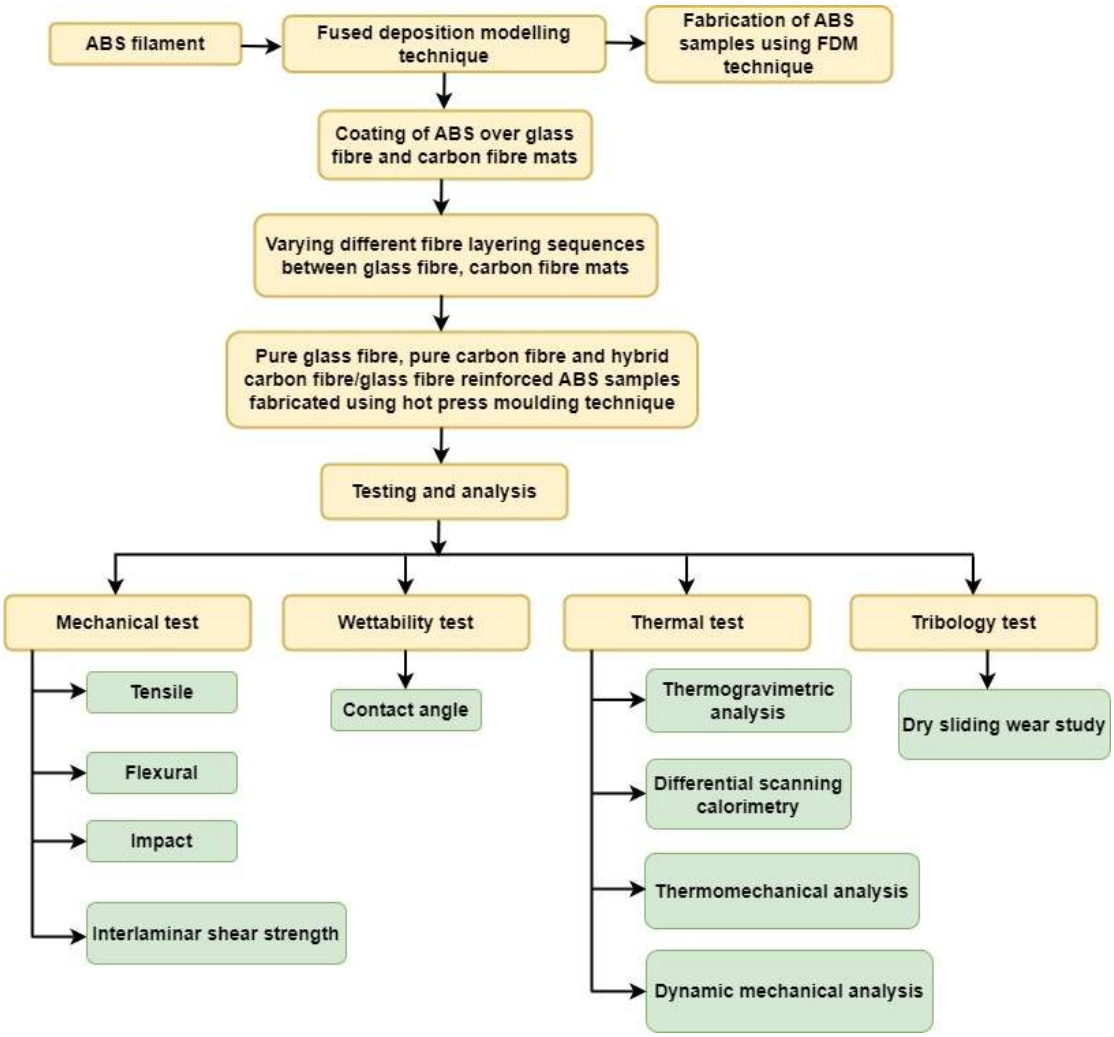

ABS filament
Fused deposition modelling technique
Fabrication of ABS samples using FDM technique
Coating of ABS over glass fibre and carbon fibre mats
Varying different fibre layering sequences between glass fibre, carbon fibre mats
Pure glass fibre, pure carbon fibre and hybrid carbon fibre/glass fibre reinforced ABS samples fabricated using hot press moulding technique
Testing and analysis
Mechanical test
Wettability test
Thermal test
Tribology test
Tensile
Flexural
Impact
Interlaminar shear strength
Contact angle
Thermogravimetric analysis
Differential scanning calorimetry
Thermomechanical analysis
Dynamic mechanical analysis
Dry sliding wear study

Figure 5.1 Research Methodology.

6. ORGANIZATION OF THESIS

Chapter 1: This chapter discusses about an overall view of composites, classification of composite materials and their applications in various fields such as aerospace, marine, automotive, construction and building, electronics, biomedical, etc. Further, synthetic fibre reinforced thermoplastic composites such as glass fibre reinforced composites, carbon fibre reinforced composites, etc. are discussed. Besides, this chapter discusses the significance of hybrid fibre reinforced thermoplastic composites and the hybrid manufacturing techniques.

Chapter 2: This chapter discusses recent literature reviews based on the mechanical, thermal, tribological behaviour of synthetic fibre reinforced thermoplastic composites. Besides, literature reviews on fabrication techniques like 3D printing techniques, hot compression and hybrid manufacturing techniques is carried out. Further, the research methodology and the research gap are presented.

Furthermore, the research objectives are also given in this chapter.

Chapter 3: This chapter discusses the details of the fibres and matrix material and the preparation of pure and hybrid samples. The fabrication procedure involving hybrid manufacturing technique is explained. The testing methods and standards for each testing are also given in this chapter.

Chapter 4: The mechanical characterization studies such as tensile analysis, flexural analysis, impact analysis and inter-laminar shear strength (ILSS) analysis. The wettability study involving contact angle testing for the ABS, GF/ABS, CF/ABS and hybrid GF/CF/ABS fibre reinforced composite samples are also discussed in this chapter. The SEM analysis was also carried out to analyse the fractured specimen of the mechanically tested composites.

Chapter 5: The thermal characterization studies such as thermogravimetric analysis (TGA), thermomechanical analysis (TMA), differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) for the ABS, GF/ABS, CF/ABS and hybrid GF/CF/ABS fibre reinforced composite samples are discussed in this chapter.

Chapter 6: The tribological characterization study involving dry sliding wear analysis for the ABS, GF/ABS, CF/ABS and hybrid GF/CF/ABS fibre reinforced composite samples are discussed in this chapter. The SEM analysis was also carried out to analyse the fractured specimen of the worn out composite samples.

Chapter 7: This chapter presents the research conclusions based on the findings, and offers potential future scope for this research.

7. Materials and methods

7.1 Materials used

ABS was used as matrix and procured from M/s Filament Wol3D, India (as shown in Figure 7.1 (a)). Bi-directional woven glass fibre (GF) (as shown in Figure

7.1(b)) and bi-directional woven carbon fibre (CF) (as shown in Figure 7.1 (c)) were used as reinforcements. These fibres were procured from M/s Rakshana Agencies, Madurai, India and M/s Vruksha Composites, Andhra Pradesh, India, respectively.

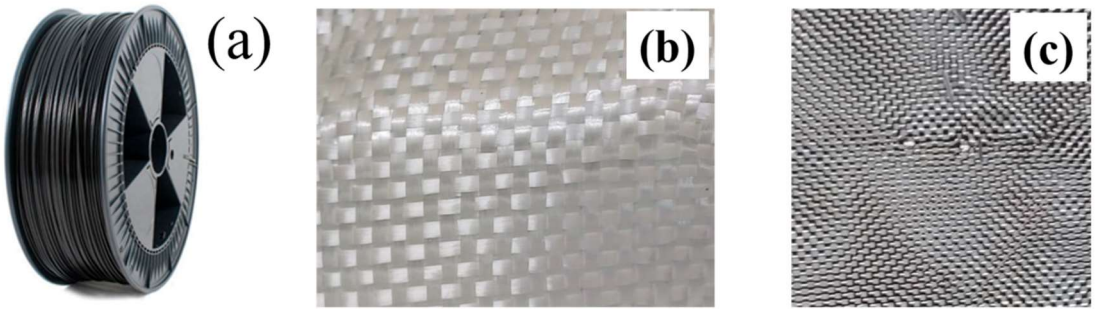


Figure 7.1 (a) ABS filament, **(b)** GF mat, and **(c)** CF mat.

Tables 7.1 and 7.2 give the mechanical and physical properties of GF, CF and ABS.

Table 7.1. Mechanical properties of glass fibre, carbon fibre and ABS.

Properties	E-Glass fibre	Carbon fibre	ABS
Tensile strength (MPa)	3100-3800	4100	≥ 43
Young's modulus (GPa)	80-81	240	1.79-3.2
Impact strength (J/m) (IZOD, 23°C, ASTM 256)	-	-	≥ 108
Flexural strength and modulus (MPa)	-	-	≥ 70 & ≥ 2300
Elongation at break %	`4.8	1.8	≥ 30

Table 7.2. Physical properties of glass fibre, carbon fibre and ABS.

Properties	Glass fibre	Carbon fibre	ABS
Melting point (℃)	Softens at 850℃, but glass does not melt. Instead, viscosity of glass fibre decreases between 1150℃ and 1250℃	Between 3650℃ and 3700℃	~200
Density (g/cm^3)	2.62	1.77	1.02
Grams per square meter (GSM)	300	200	-

7.2 Composite fabrication using hybrid manufacturing technique

The fabrication of GF/ABS, CF/ABS, and their hybrid combinations was carried out using two distinct processing methods: fused deposition modeling (FDM), and hot pressing. Figure 7.2 (a–g) depict the sequential stages involved in the fabrication of the composite material.

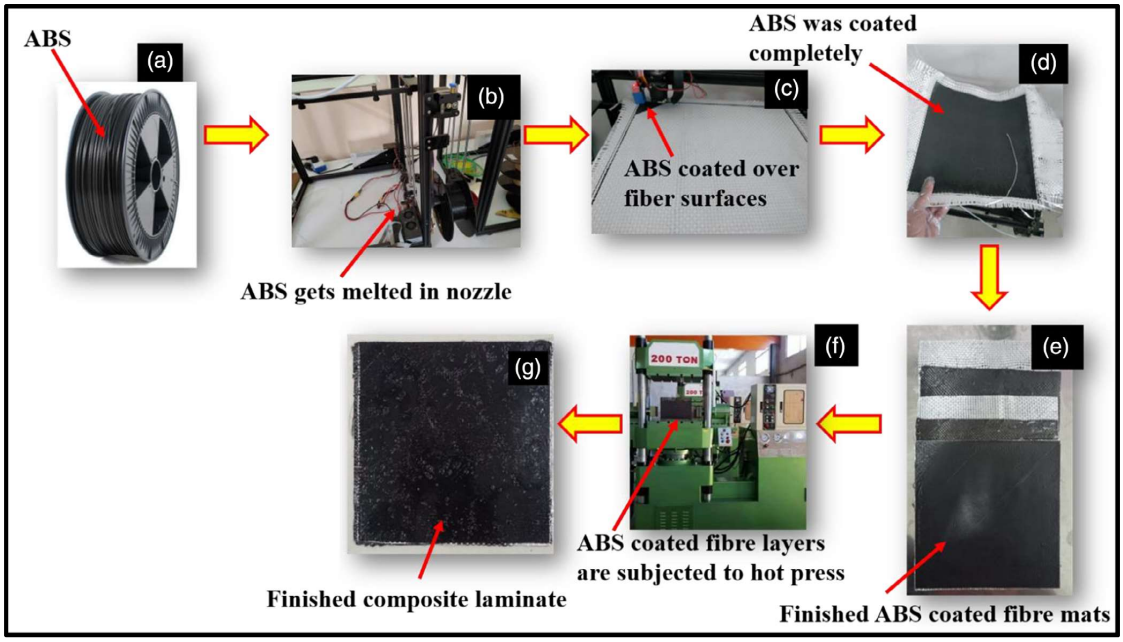


Figure 7.2. ABS filament (a), ABS gets melted in a nozzle, and the melted materials are deposited over the fibre mats (b), the progress of ABS coated over the fibre mats (c, d), coated fibre mat layers (e), coated fibre mat layers are subjected to hot compression (f), finished composite laminate (g).

7.2.1 FDM technique

ABS coating was applied to the GF and CF layers using a 3D printer (JB Technology, Coimbatore, India; model number: XL300) at JB Technology, 3D Printing Services, Coimbatore, India. For example, in the fabrication of GF/ABS composites, a total of five GF layers was utilized, with the ABS layer maintained at a thickness of 0.3 mm. Similarly, CF/ABS composite laminates were fabricated. The number of layers and fibre layering sequence for GF/ABS, CF/ABS, and GF/CF/ABS are presented in Tables 7.3 (a-c). When applying the ABS coating over glass or carbon fibre layers using the FDM technique, it was important to maintain a printing speed of 35 mm/s and a nozzle temperature of 90° C in order to ensure proper adhesion between the ABS coating and the fibre layers. The slower printing speed allowed for better control over the extrusion of the ABS, which could help to

prevent over-extrusion and ensure a consistent layer thickness. A nozzle temperature of 235° C was also maintained to ensure that the ABS was heated to the appropriate temperature for proper melting and extrusion, which could help to ensure good adhesion between the ABS and the fibre layers. These ABS-coated samples were subsequently subjected to a hot press technique.

Table 7.3. (a) Fabrication details of GF/ABS matrix composites

Layer details	Matrix and fibre details	Composite configuration
1st layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	GF/ABS
2nd layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	
3rd layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	
4th layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	
5th layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)/ 3D printed ABS (0.3mm)	

Table 7.3. (b) Fabrication details of CF/ABS matrix composites

Layer details	Matrix and fibre details	Composite configuration
1st layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	CF/ABS
2nd layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	
3rd layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	
4th layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	
5th layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)/ 3D printed ABS (0.3mm)	

Table 7.3. (c) Fabrication details of GF/CF/ABS matrix composites

Layer details	Matrix and fibre details	Composite configuration
1st layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	GF/CF/ABS
2nd layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	
3rd layer	3D printed ABS (0.3mm)/Glass fibre (0.4mm)	
4th layer	3D printed ABS (0.3mm)/Carbon fibre (0.4mm)	
5th layer	3D printed ABS (0.3mm) /Glass fibre (0.4mm)/ 3D printed ABS (0.3mm)	

7.2.2 Hot press technique

The ABS coated fibre layers such as GF, CF, and GF/CF were loaded separately into a hydraulic press machine. After positioning the fibre layers in the press, the pressure and temperature were set to 1000psi and 230° C, respectively, for a period of five minutes. During this process, the ABS coating gets liquified and penetrated through each layer before curing.

The composite laminate samples were removed from the press and underwent post-curing at 60°C for 24 hours. During post-curing, the heat can cause the ABS matrix to further crosslink and form stronger bonds between the GF, CF and matrix.

The process of post-curing can result in improved strength, helps to remove any remaining volatiles that may have been trapped in the laminate during the initial curing process. It also ensures that the laminate has been fully cured and has reached the desired mechanical properties. The ratios of fibre and matrix, such as GF, CF, and ABS are presented in Table 7.4.

Table 7.4. Details of fibre and matrix weight reinforcement ratios.

Type of composites	Weight (g)			Weight fraction (%)		
	Wt_G	Wt_c	Wtm	WF_G	WF_c	WFm
Neat ABS	-	-	140	-	-	100
GF/ABS	136	-	84	61.84	-	38.18
CF/ABS	-	162.5	84	-	65.92	34.08
GF/CF/ABS	81.6	65	84	35.34	28.19	36.43

Where, f = fabric; G = Glass fibre; C = Carbon fibre; m = matrix

Wt_G = Weight of glass fibre; Wt_C = Weight of carbon fibre;

WF_G = Weight fraction of glass fibre; WF_C = Weight fraction of carbon fibre;

7. Results and discussions

Figure 8.1 (a) and 8.1 (b) indicates that,

- GF/ABS composites achieved the best tensile strength and elongation at break. For instance, the tensile strength of ABS was improved from 25.64 MPa to 151.8 MPa. Similarly, 43% improvement was noticed in elongation at the break values of ABS composites after the samples were reinforced with GF. GF/CF/ABS achieved next better values (tensile strength of 2196 MPa and 29% of elongation at break)
- CF/ABS composites achieved the highest tensile modulus. For instance, the tensile modulus of ABS was improved from 625.2 MPa to 3118 MPa. GF/ABS achieved next better value of 2586 MPa.

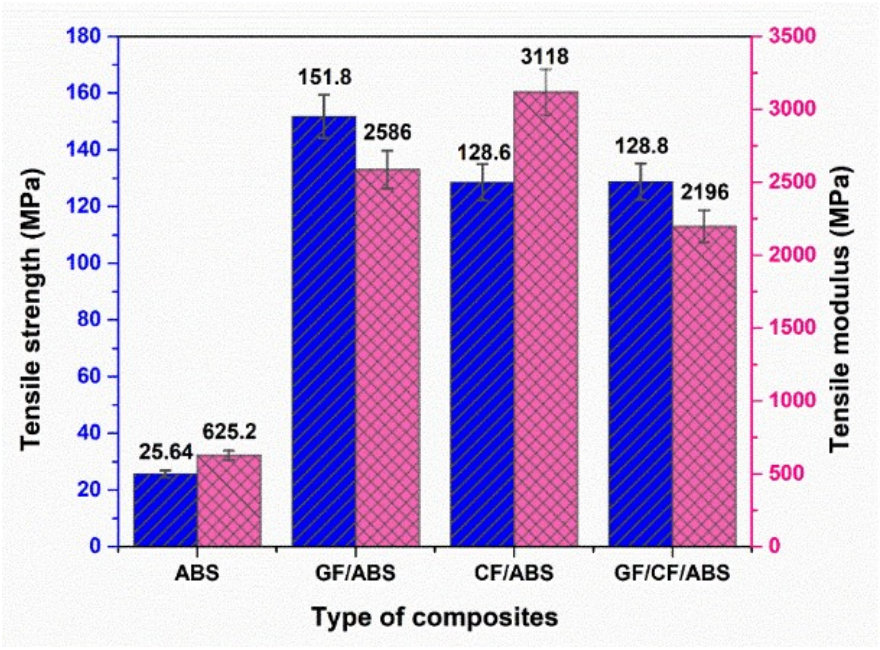


Figure 8.1. (a) Tensile strength and tensile modulus of the samples

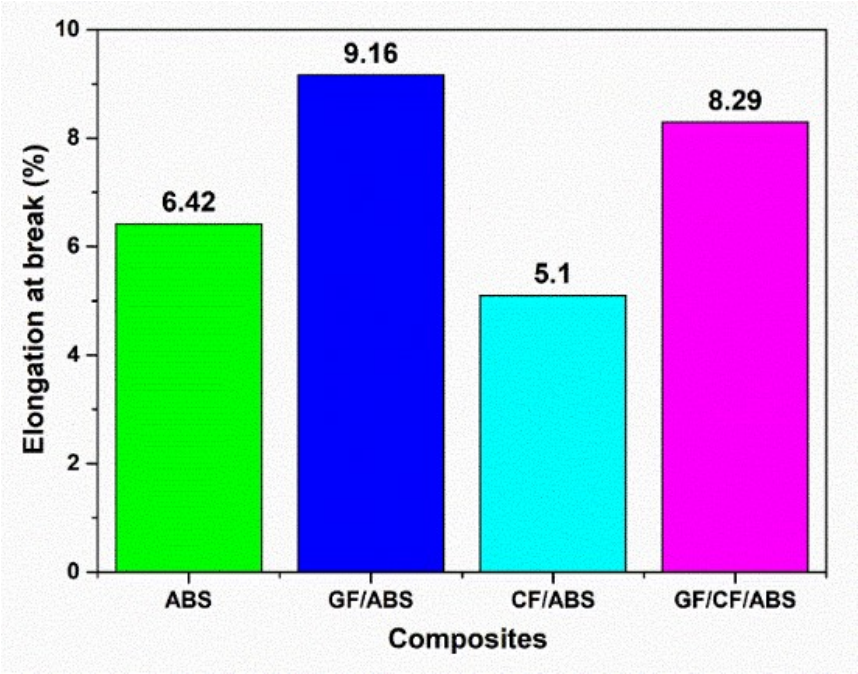


Figure 8.1. (b) Percentage of elongation at break of the samples

Figure 8.2 indicates that,

- The sample of GF/ABS showed higher values for flexural strength and flexural modulus, measuring 64.46 MPa and 3549.71 MPa, respectively, compared to the other samples tested.

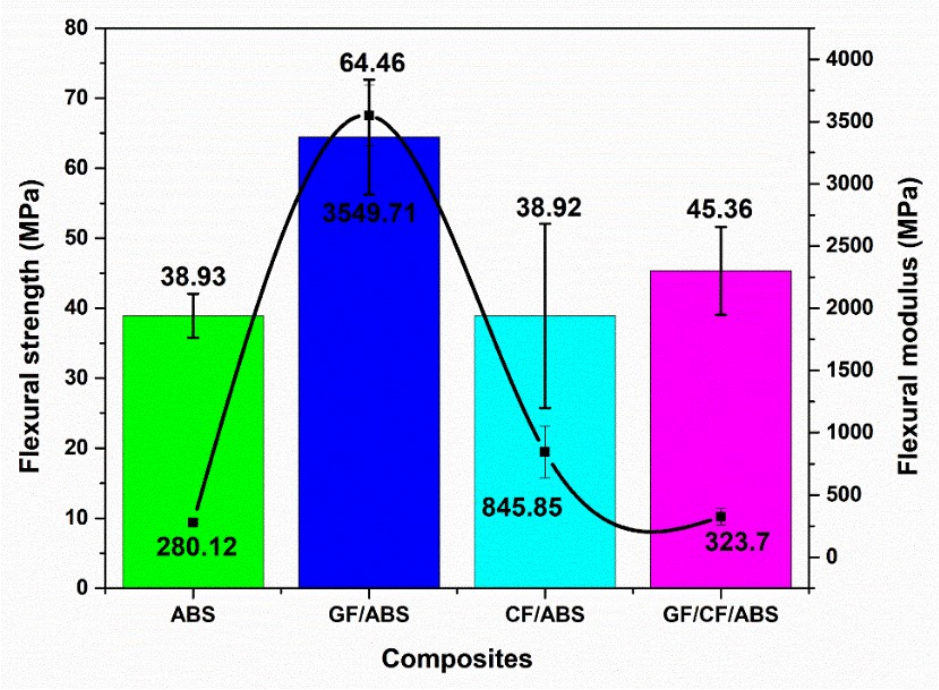


Figure 8.2. Flexural strength and modulus of the samples

Figure 8.3 indicates that,

- The impact strength of the CF/ABS and GF/CF/ABS composites was lowered due to the incorporation of brittle CF in the ductile ABS matrix. Similar to its flexural behavior, the GF/ABS sample also exhibited higher impact strength, measuring 0.089 J/mm^2, compared to the other samples tested.

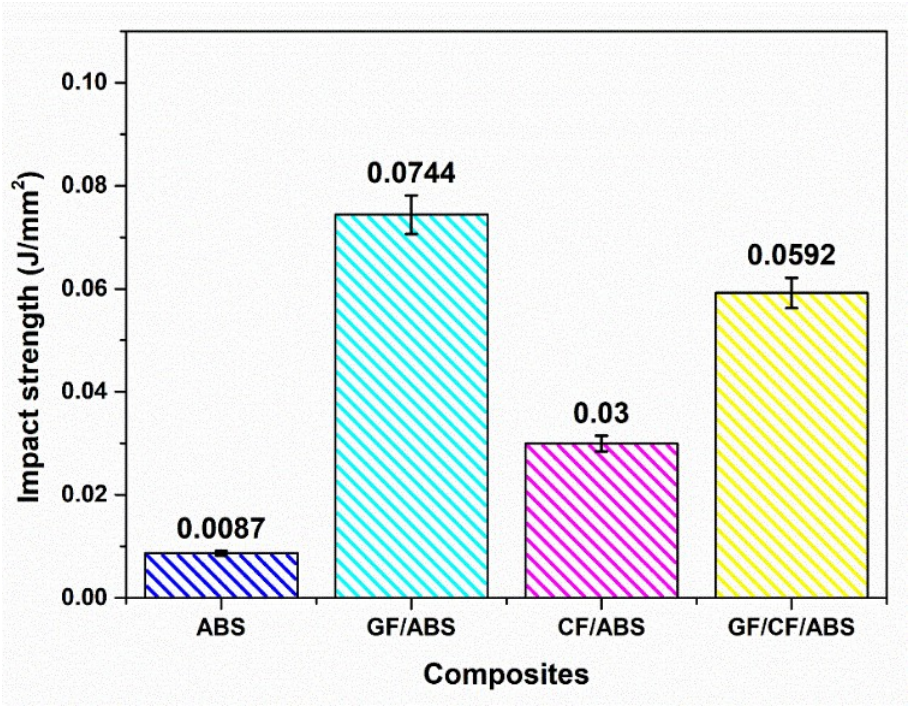


Figure 8.3. Impact strength of the samples

Figure 8.4 indicates that,

- The ILSS shows an increasing trend as: CF/ABS<ABS<GF/ABS<GF/CF/ABS. The percentage of increase reported as highest between virgin ABS and composite was 217% (ABS to GF/CF/ABS).

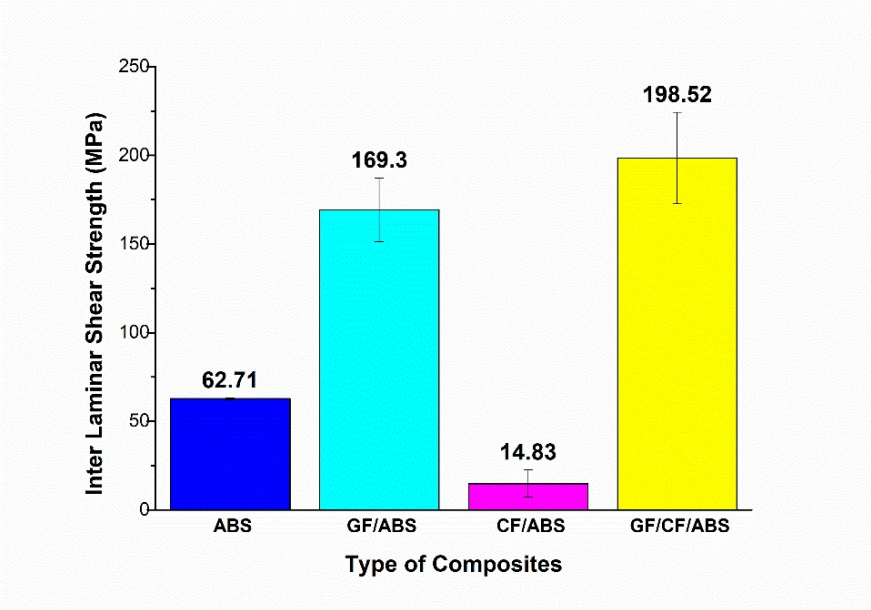


Figure 8.4. Interlaminar shear strength of the samples

Figure 8.5 indicates that,

- The contact angle achieved followed the sequence: ABS<GF/ABS< CF/ABS<GF/CF/ABS, which shows hydrophobic behaviour of composite increased with addition of fibres.

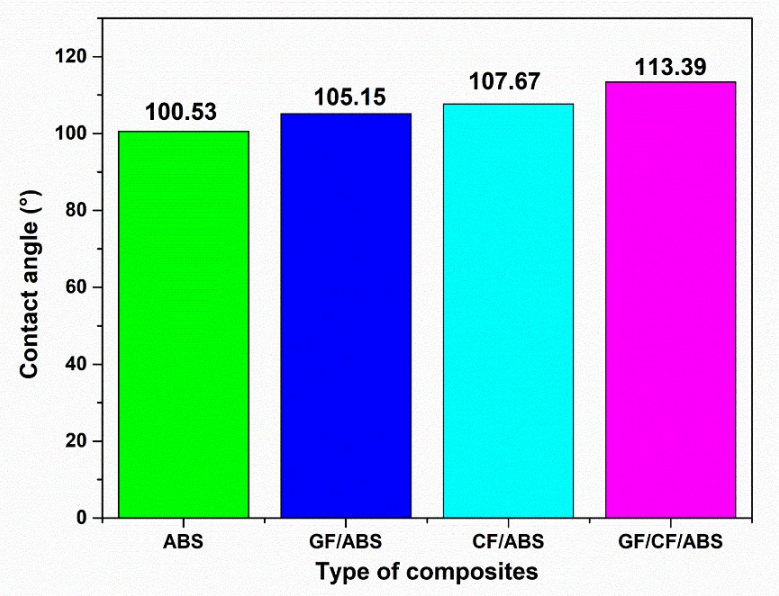


Figure 8.5 Contact angle of the samples

Figure 8.6 (a), 8.6 (b) and 8.7 indicates that,

- The thermogravimetric and differential scanning calorimetry suggested that the CF/ABS exhibited better performance by giving higher degradation temperatures and increased glass transition temperature value (109.83°C).

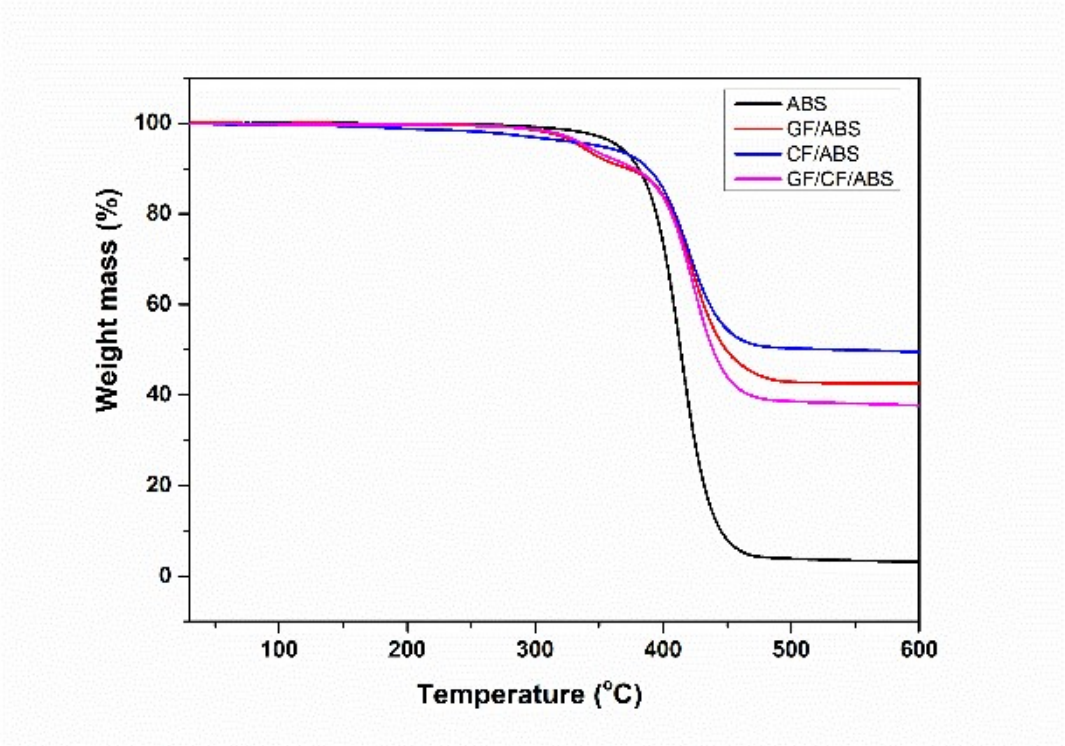


Figure 8.6. (a) TGA primary thermogram of the samples

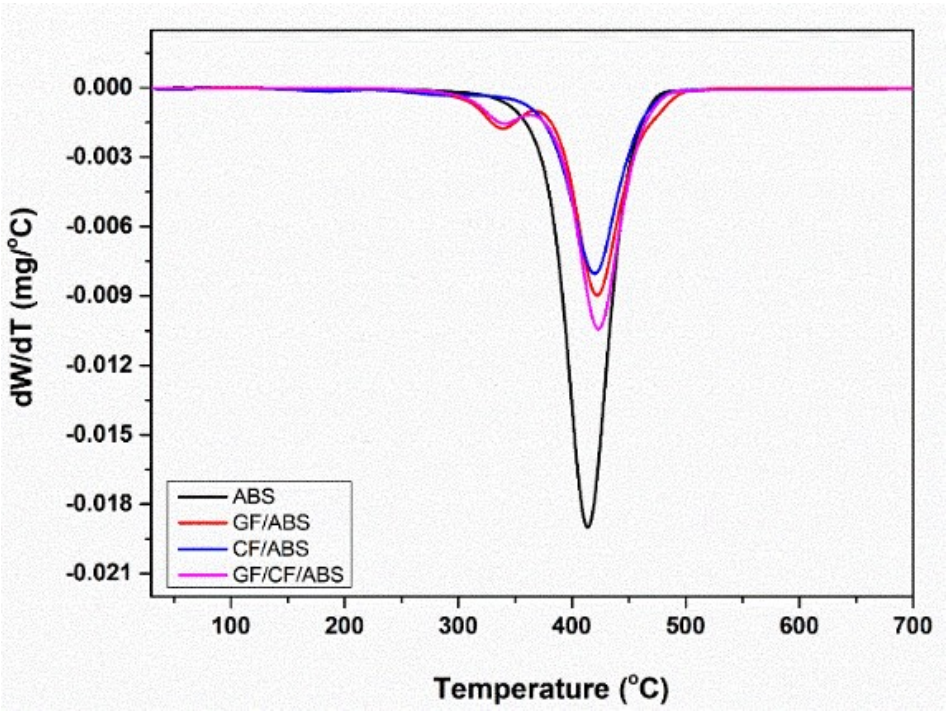


Figure 8.6. (b) TGA secondary thermogram of the samples

- However, the difference between ABS, GF/ABS and hybrid composites was less.

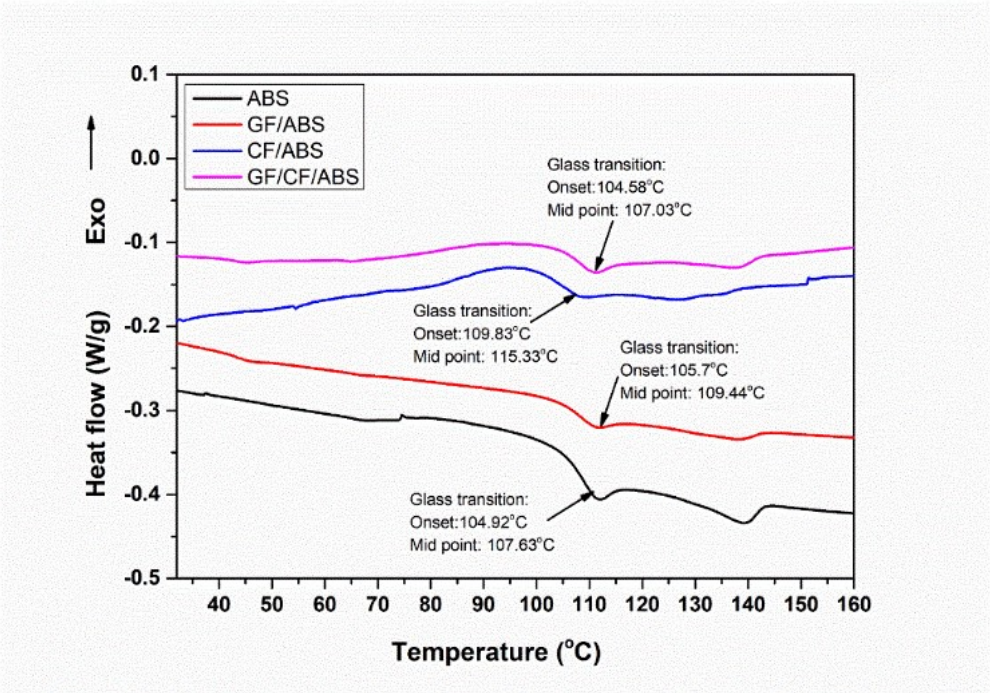


Figure 8.7 DSC plot of the samples

Figure 8.8 indicates that,

- In the thermomechanical analysis, the carbon fibre/ABS showed enhanced thermal expansion behaviour. For instance, the dimensional change followed the sequence: CF/ABS < GF/CF/ABS < GF/ABS <ABS.

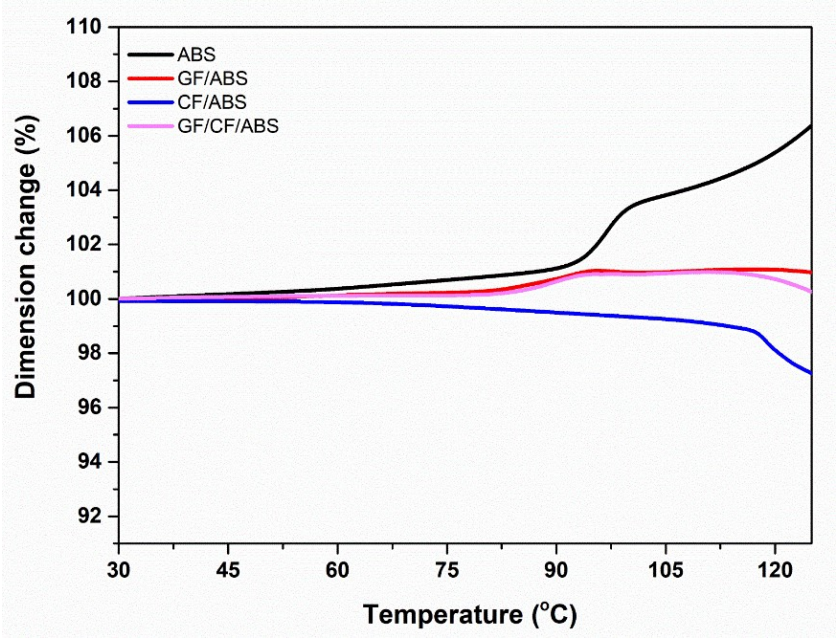
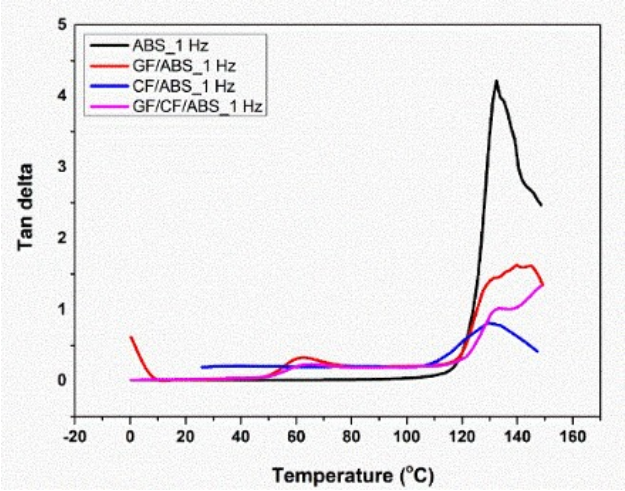


Figure 8.8. Thermal expansion /Shrinkage of the samples

Figure 8.9. (a) Tan Delta of different of the samples at frequency of 1 Hz

Figure 8.9 (a-c) indicates that,

- In DMA analysis, the results reported higher values of E′, E”, and tan delta for the operating frequency of 10 Hz.



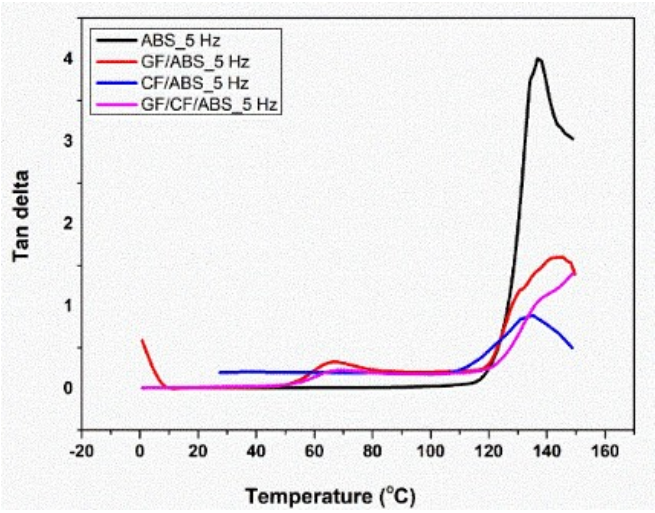


Figure 8.9. (b) Tan Delta of different of the samples at frequency of 5 Hz

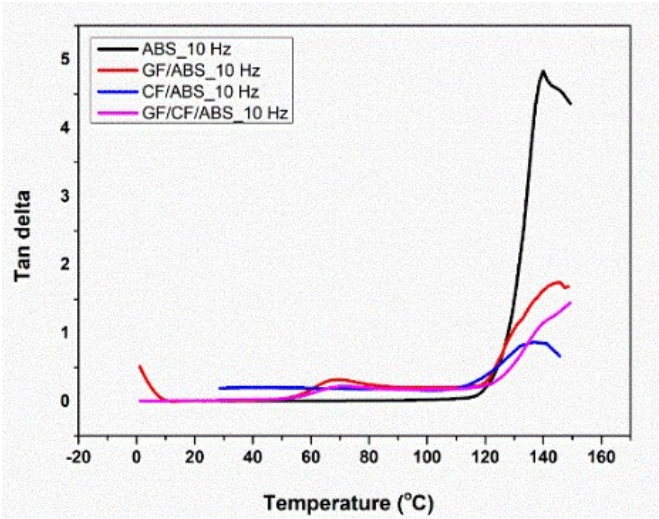


Figure 8.9. (c) Tan Delta of different of the samples at frequency of 10 Hz

Figure 8.10 (a-c) indicates that,

- The study found that the wear loss of the composite laminates was lower compared to that of the ABS samples. At higher velocity GF/ABS composite laminates exhibited the lowest wear loss of 23 μm (5 N and 4 m/s) among all the tested samples. The wear loss increased as the load increased from 5 N to 10 N for all GF/ABS, CF/ABS and GF/CF/ABS samples.

Figure 8.11 (a-c) indicates that,

- The coefficient of friction of the ABS samples was lower, with a value of 0.295 at 4 m/s under a 5 N load. The composite laminates also showed a lower coefficient of friction at 4 m/s for both 5 N and 10 N loads. Among the different loaded samples, the CF/ABS samples showed the lowest coefficient of friction.

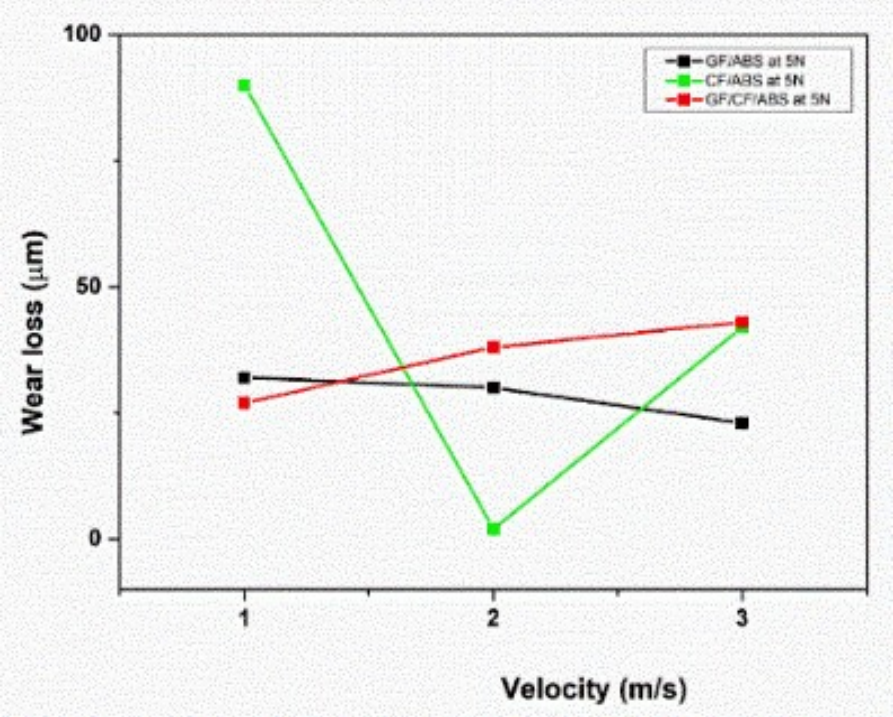


Figure 8.10. (a) Wear loss of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 5 N

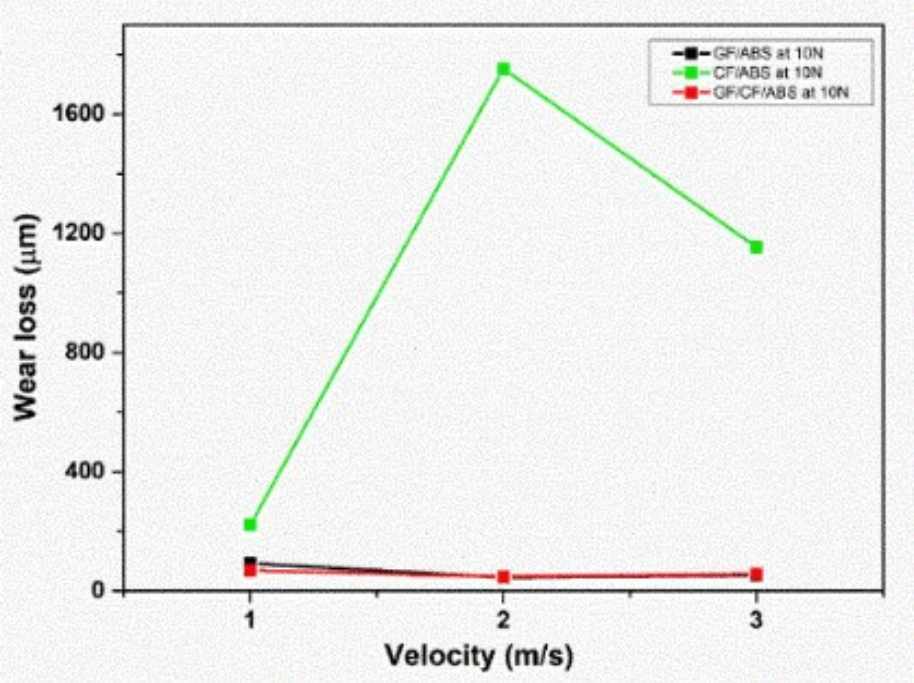


Figure 8.10. (b) Wear loss of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 10 N

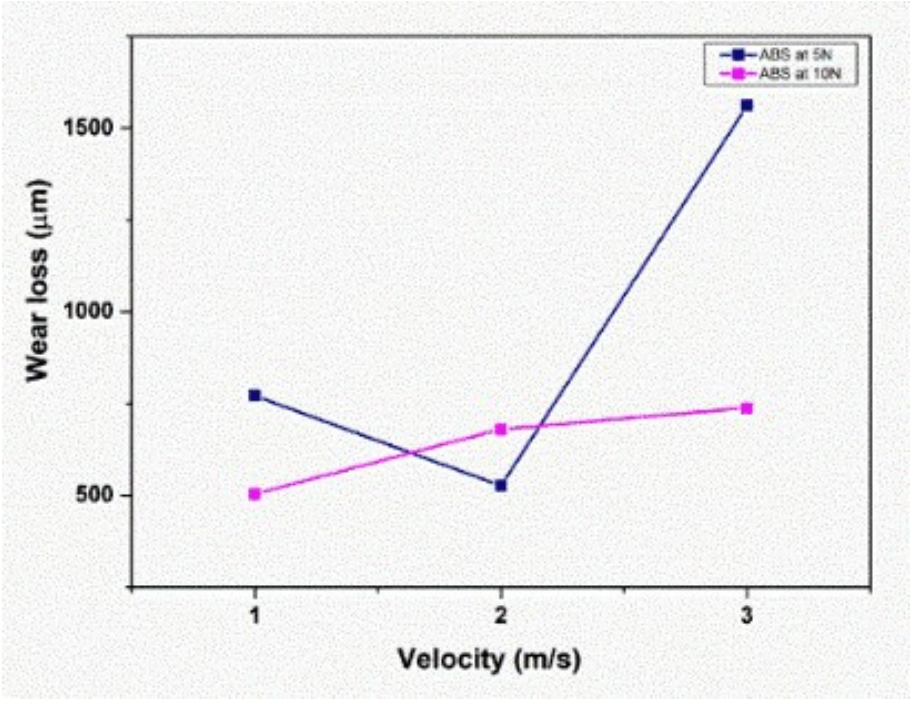


Figure 8.10. (c) Wear loss of the ABS sample at a load of 5 N and 10 N

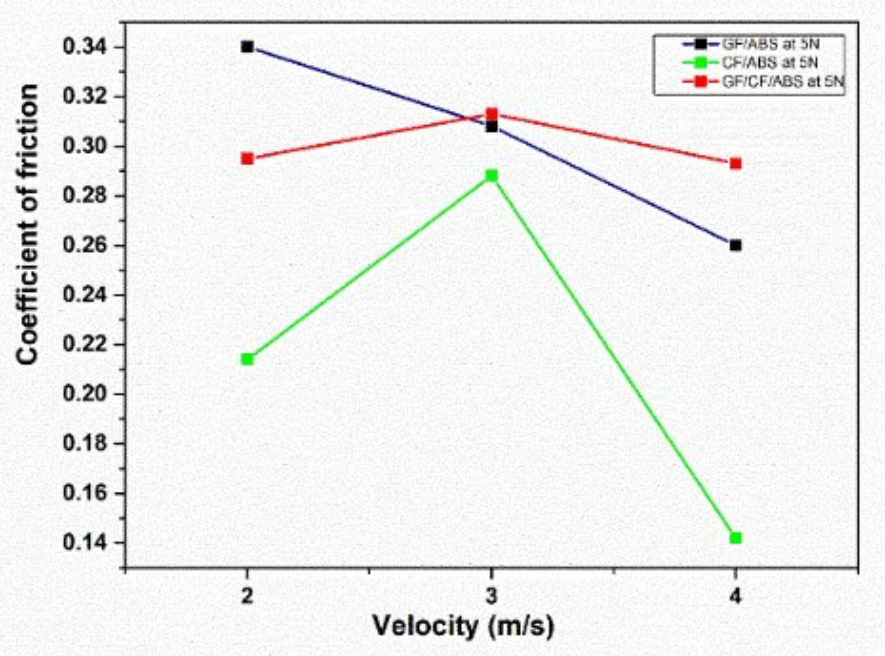


Figure 8.11. (a) Coefficient of friction of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 5 N

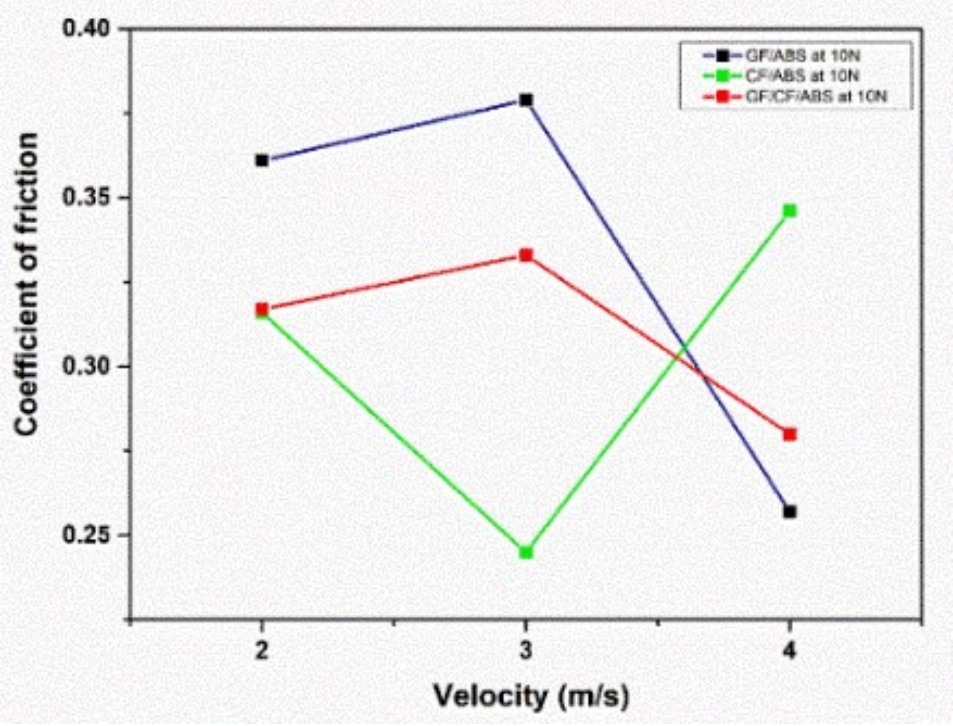


Figure 8.11. (b) Coefficient of friction of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 10 N

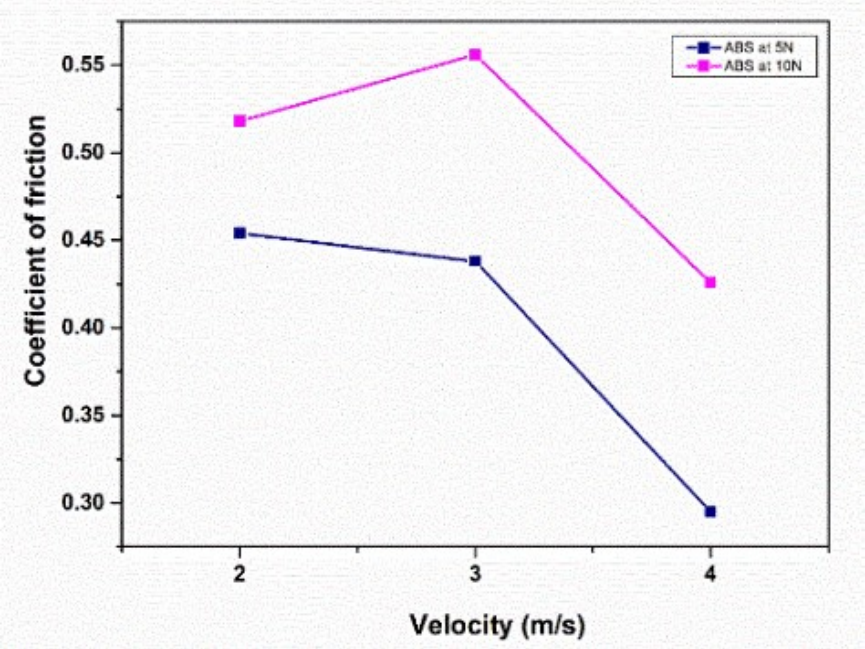


Figure 8.11. (c) Coefficient of friction of the ABS sample at a load of 5 N and 10 N

Figure 8.12 (a-c) indicates that,

- The ABS samples showed lower friction force values at 2 m/s to 4 m/s under 5 N of load, with a friction force of 1.5 measured for ABS samples (5 N and 2 m/s). In the composite laminates, the CF/ABS exhibited a lower friction force under a 5 N load. When the load was increased from 5 N to 10 N, the friction force increased.

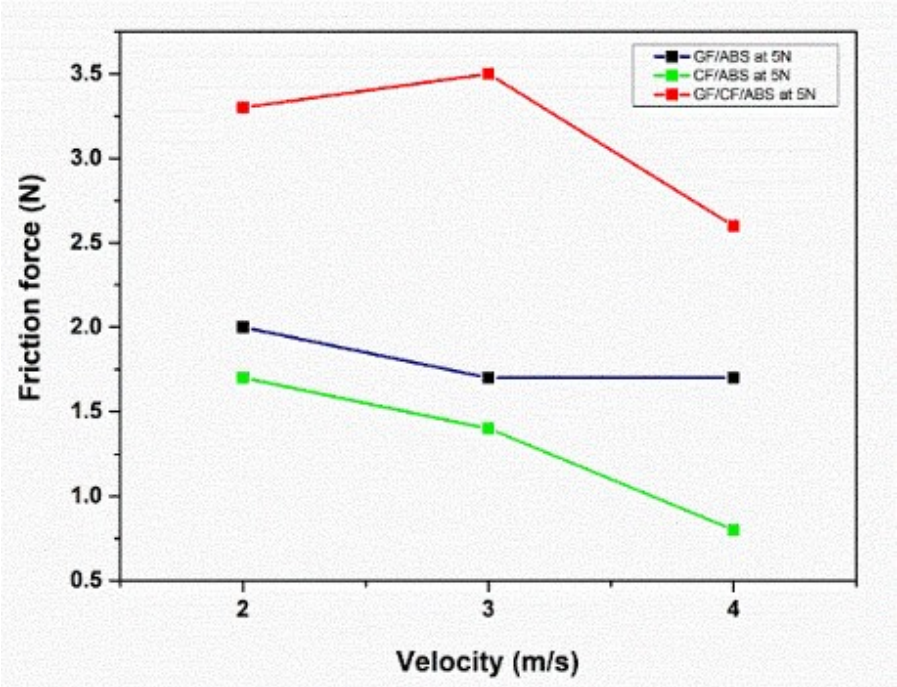


Figure 8.12. (a) Friction force of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 5 N

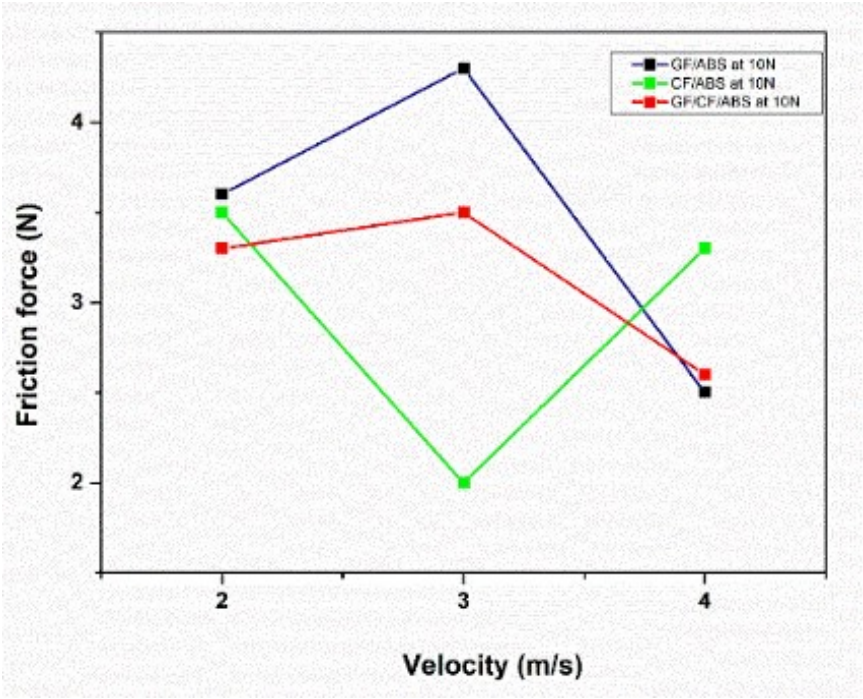


Figure 8.12. (b) Friction force of the GF/ABS, CF/ABS, GF/CF/ABS samples at a load of 10 N

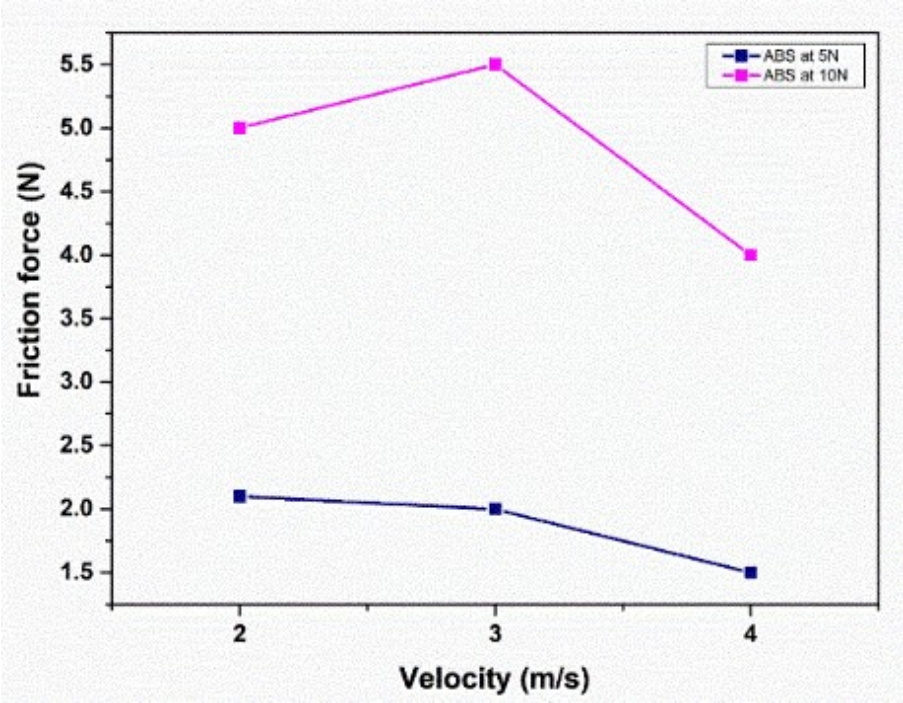


Figure 8.12. (c) Friction force of the ABS sample at a load of 5 N and 10 N

9. Limits and Future works

One of the main limitations is the cost involved in 3D printing the composites, particularly when using ABS, which can be expensive. However, these limitations can be addressed by implementing large-area manufacturing and mass production

techniques. The future research should focus on optimizing the manufacturing process to reduce costs and increase efficiency while exploring the potential use of these composites in a wider range of applications. Perspectives for future research include expanding the investigation to examine the effects of fibre-matrix combinations on other important properties. Furthermore, investigating the effects of processing parameters such as printing speed and temperature on the mechanical properties of the composites could provide valuable insights into the behavior of the materials in different conditions. Further study would involve adding fillers to improve the mechanical and thermal behaviour of glass fibre/ABS and glass fibre/carbon fibre/ABS hybrid composites.

10. Conclusions

The hybrid manufacturing technique combining FDM and hot press molding demonstrated competitive results in fabricating composite laminates. Future studies can focus on optimizing the manufacturing process to further enhance the mechanical properties of the composite laminates. The strength can be improved by incorporating tougher and more ductile materials in the composite matrix. In addition, the frequency-dependent behavior of the composites can be further explored to determine the ideal operating frequency for specific applications. Overall, the findings of this study contribute to the growing interest in 3D printed composites and demonstrate the potential of the hybrid manufacturing technique in producing competitive results. Further research can build on these findings to design and develop composites with improved properties for various applications.

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Book Chapter

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